ELECTRO-OPTICAL DEVICES FROM POLYMER-STABILIZED LIQUID CRYSTAL MOLECULES

Background

The present invention relates to the liquid crystal arts. It particularly relates to liquid crystal modulators for applications such as optical waveguides, optical beam scanners, computer-generated holograms, adaptive optics, flat-panel liquid crystal 5 displays, and the like. However, the invention will also find application in conjunction with other electro-optical devices employing liquid crystals.

Liquid crystal materials include anisotropic molecules that can be electrically or magnetically aligned, tilted, rotated, or otherwise manipulated. For example, in nematic liquid crystal phases, the long axis of the anisotropic molecules are 10 generally aligned, but there is substantially no translational ordering. In smectic liquid crystal phases, the long axis of the anisotropic molecules are generally aligned, and additionally some translational ordering is present.

In chiral or cholesteric liquid crystal phases, a mesoscopic helical ordering is also present. The long axis alignment of molecules is relatively rotated 15 between successive layers of molecules, creating a helical rotation along a helix direction that is generally transverse to said layers. A helical pitch is defined as the average distance along the helix direction over which the relative rotation of successive layers corresponds to a complete 360° helical rotation of the anisotropic molecules. For short helical pitches of around 0.2-0.5 micron, the helical characteristic optically 20 manifests as uniaxial birefringence with an optic axis along the helix direction.

In one typical electro-optic device, liquid crystal material is disposed between spaced apart confining surfaces, such as glass surfaces, at least one of which is light transmissive. For light transmission applications, both spaced apart confining

surfaces are light transmissive. To induce lateral ordering of the anisotropic liquid crystal molecules, one or both confining surfaces are preferably anisotropic surfaces. For example, a thin polymer coating such as a polymide can be spread on the exemplary glass substrate and rubbed in a selected direction to provide a suitable anisotropic surface for inducing substantial lateral ordering of the liquid crystal molecules.

In the case of short-pitch chiral or cholesteric liquid crystal devices, the helix direction can be aligned perpendicular to the confining surfaces (called a Gradjean texture) or can be aligned parallel to the confining surfaces (called a fingerprint texture). Typically, the fingerprint texture has the helix axes randomly distributed with no long-range ordering in the plane of the confining surface. However, in electro-optic devices the rubbed or otherwise anisotropic surface preferably induces a uniformly lying helix texture in which the helix axis lies parallel to the confining surfaces along a selected helix alignment direction.

The uniformly lying helix texture is optically uniaxially birefringent with an optic axis along the helix alignment direction. In some liquid crystal materials arranged in a uniformly lying helix texture, application of a relatively small electric field directed perpendicular to the confining surfaces induces a flexoelectric in-plane deviation of the optical axis. For higher electric fields, dielectric coupling is present and the helix begins to unwind. At sufficiently high electric field, the helix is substantially completely unwound, producing a homeotropic texture.

For electro-optic device applications, a problem arises in that the unwinding of the helix is generally not completely reversible, and can produce degradation of alignment by the confining surfaces since either the planar or homeotropic surface condition supports the unwound helical structure in the uniformly lying helix texture, and the like. As a result, the electro-optic device does not fully return to the uniformly lying helix texture after the applied electric field is removed.

To address such problems, polymer stabilization of the uniform lying helix texture has been employed. In one configuration described in P. Rudquist, L. Komitov, and S.T. Lagerwall, Liquid Crystals volume 24, page 329 (1988), 10wt% of a photoreactive monomer dissolved into a cholesteric liquid crystal was optically polymerized to produce a stabilizing polymer network which provided effective stabilization of the uniformly lying helix texture. However, the polymer network

produced substantial residual birefringence that decreased cell contrast in the unwound state. This residual birefringence substantially decreased contrast and modulation efficiency and degraded switching time of electro-optic switching devices.

The present invention contemplates an improved apparatus and method which overcomes the aforementioned limitations and others.

Summary

According to one aspect, an electro-optic device is disclosed. First and second spaced-apart surfaces define a gap. A chiral or cholesteric liquid crystal material is disposed in the gap. A polymeric network is disposed in the gap. The polymeric network is less than or about 5 weight percent of the liquid crystal. The polymeric network biases the liquid crystal material toward a substantially uniformly lying helix texture.

According to another aspect, an electro-optic method is provided. A chiral or cholesteric liquid crystal, a photoreactive monomer, and a photoinitiator are disposed in a liquid crystal cell. A principal surface of the liquid crystal cell is illuminated with ultraviolet light selected to have a non-uniform ultraviolet light intensity profile in the liquid crystal cell. The illuminating cooperates with the photoinitiator to polymerize at least a portion of the photoreactive monomer near the principal surface to generate a polymer network having a density corresponding to the non-uniform ultraviolet light intensity profile. The polymer network biases the liquid crystal toward a selected helical alignment direction.

According to yet another aspect, a method for fabricating an electo-optic device is provided. A liquid crystal and a photoreactive monomer are disposed in a liquid crystal cell. The disposed photoreactive monomer is less than 5 weight percent of the disposed liquid crystal. The liquid crystal is arranged in a uniformly lying helix texture. The photoreactive monomer is optically polymerized to form a stabilizing polymer network.

According to still yet another aspect, an electro-optic device is disclosed, including: a liquid crystal cell; at least one electrode arranged to selectively electrically bias the liquid crystal cell; a chiral or cholesteric liquid crystal disposed in the liquid crystal cell, the liquid crystal having an optic axis substantially along a selected optic

axis direction in the absence of an electrical bias; and a polymeric network disposed at an inside surface of the liquid crystal cell, the polymeric network extending partway into the liquid crystal cell leaving at least a portion of the liquid crystal cell substantially free of the polymeric network.

5   Numerous advantages and benefits of the present invention will become apparent to those of ordinary skill in the art upon reading the following detailed description of the preferred embodiment.

Brief Description of the Drawings

The invention may take form in various components and arrangements

10   of components, and in various process operations and arrangements of process operations. The drawings are only for the purpose of illustrating preferred embodiments and are not to be construed as limiting the invention.

FIGURE 1 shows a cross-sectional view of an electro-optic device employing a stabilizing single-surface polymer network.

15   FIGURE 2 shows a cross-sectional view of an electro-optic device employing a stabilizing double-surface polymer network.

FIGURE 3 shows a cross-sectional view of an electro-optic device employing a stabilizing volume polymer network.

FIGURE 4 shows switching behavior of a volume-stabilized

20   electro-optic device responsive to a square wave voltage input.

FIGURE 5 shows switching behavior of a volume-stabilized electro-optic device responsive to a triangle wave voltage input.

FIGURE 6 shows switching behavior of a double-surface-stabilized electro-optic device responsive to a square wave voltage input.

25   FIGURE 7 shows switching behavior of a double-surface-stabilized electro-optic device responsive to a triangle wave voltage input.

Detailed Description of the Preferred Embodiments

With reference to FIGURES 1-3, three example electro-optic devices are described. The example devices of FIGURES 1 and 2 are known in the art as

30   surface-stabilized devices in which a stabilizing polymer network is substantially

restricted to a surface sub-region. The example device of FIGURE 3 is known in the art as a volume-stabilized device in which the stabilizing polymer network is substantially uniform throughout the liquid crystal. It will be appreciated that the polymer networks of FIGURES 1 and 2 are not drawn to scale, and typically reside close to the confining surfaces, that is, within a thin surface sub-region. However, it is also to be appreciated that a continuum of polymer network distributions can exist ranging from a network confined very close to the confining surfaces to the spatially uniform volume-stabilized device of FIGURE 3. Thus, the term "surface-stabilized sub-region" does not define any particular thickness of the region containing the polymer network.

With reference to FIGURE 1, a surface-stabilized electro-optic device includes a liquid crystal cell 10 having two spaced apart principal confining substrates 12, 14, at least one of which is light-transmissive, and confining side surfaces 16, 18. For light transmission applications, both confining substrates 12, 14 should be light-transmissive. In one suitable embodiment, the confining surfaces 12, 14 are glass plates. Electrodes 20, 22 are disposed on facing surfaces of the confining substrates 12, 14. In one embodiment the electrodes 20, 22 are substantially light-transmissive metal oxide films. At least one of the two spaced apart principal confining substrates 12, 14, specifically the substrate 14 in FIGURE 1, includes an anisotropic alignment surface 24 with an anisotropic surface morphology produced by rubbing, anisotropic chemical etching, or the like. In one embodiment the anisotropic alignment surface 24 is provided by spreading a thin polymer coating such as a polymide on the electrode 22 and glass substrate 14, and rubbing the polymer coating in a selected rubbing direction to induce surface anisotropy. A gap G is defined between facing confining surfaces of the two spaced apart principal confining substrates 12, 14.

Within the gap G a liquid crystal material 30 is disposed. The liquid crystal 30 is preferably a chiral liquid crystal such as a cholerestic liquid crystal material, a smectic C* phase liquid crystal material, or the like, which possess a helical molecular order. The liquid crystal 30 is further preferably a short-pitch chiral or cholesteric liquid crystal. The short pitch preferably is less than about 0.5 microns, and more preferably is between about 0.2 microns and about 0.5 microns. However, longer-pitch chiral or cholesteric liquid crystal materials can be used. The liquid crystal material 30 preferably exhibits birefringence for visible light when in the chiral or

cholesteric liquid crystal phase, but preferably does not exhibit substantial birefringence when electrically biased into an unwound or homeotropic texture phase.

The liquid crystal material 30 preferably has a uniformly lying helical texture in which the helix axis of the chiral or cholesteric liquid crystal 30 lies parallel to the principal confining substrates 12, 14 along a selected helical alignment direction. Depending upon the pitch of the chiral or cholesteric liquid crystal 30 and the size of the gap G, the selected helical alignment direction can be oriented parallel or perpendicular to the rubbing direction or other anisotropic direction defined by the anisotropic alignment surface 24.

A stabilizing polymer network 32, indicated diagrammatically in FIGURE 1, is disposed adjacent the anisotropic alignment surface 24 and extends partway into the gap G. Although FIGURE 1 shows a disordered stabilizing polymer network 32, it is also contemplated to use a partially or fully ordered stabilizing polymer network in which, for example, the polymer chains are aligned generally perpendicularly to the confining surfaces 12, 14. The stabilizing polymer network 32 preferably is less than about 5 weight percent (5wt%) of the liquid crystal material 30, and more preferably is less than about 3 weight percent (3wt%) of the liquid crystal material 30.

At least one electrode is provided to electrically bias the gap G. Preferably, the pair of electrodes 20, 22 selectively produce an electric field within the gap G directed generally transverse to the facing confining surfaces of the substrates 12, 14. If during electro-optic operation light passes through the confining surface on or in which an electrode is disposed, then the electrode should be substantially light transmissive. For example, a substantially transparent indium tin oxide film can be used, the electrode can be a substantially light transmissive thin metal film, or the electrode can be a gridded electrode having openings for light to pass through.

In one embodiment, the stabilizing polymer network 32 is formed as follows. Initially, a photoreactive monomer is dissolved in the liquid crystal material 30. The uniformly lying helical texture is produced by heating, electrical biasing using electrodes 20, 22, or a combination thereof. The stabilizing polymer network 32 is formed by optically polymerizing the photoreactive monomer using ultraviolet light 46 (indicated diagrammatically by dashed arrows in FIGURE 1). To promote the optical

polymerizing, a photoinitiator is preferably dissolved into the liquid crystal material **30**. In a typical chemical reaction leading to optical polymerization, the monomer includes photoreactive ends that bind with the photoinitiator.

A photon energy or free-space wavelength of the ultraviolet light **46** is selected to have a non-uniform ultraviolet light intensity profile **50** in the liquid crystal material **30**. The non-uniform ultraviolet light intensity profile **50** is graphically indicated in FIGURE 1 at the left-side of the liquid crystal cell **10**, and has a generally exponentially decaying shape according to:

$$I(x) = I_o \cdot e^{-\alpha x} \tag{1},$$

where I_0 is an initial intensity of the ultraviolet light **46** just inside the anisotropic alignment surface **24**, the "x" is a distance measured from just inside the anisotropic alignment surface **24**, I(x) is the ultraviolet light intensity profile, and α is an absorption coefficient of the ultraviolet light **46** in the liquid crystal material **30**.

The ultraviolet light **46** is preferably produced by an ultraviolet fluorescent tube, although an ultraviolet laser or other ultraviolet source can be used. Because the absorption coefficient α is generally wavelength dependent, in the case of a polychromatic ultraviolet source a wavelength-selective filter is preferably inserted between the ultraviolet source and the liquid crystal cell **10** to provide monochromatic ultraviolet light **46**.

In exemplary FIGURE 1, the exponential intensity decay of the ultraviolet light **46** in the liquid crystal material **30** results in a density profile of the stabilizing polymer network **32** that generally corresponds with the non-uniform ultraviolet light intensity profile **50** of the ultraviolet light **46**. This causes the stabilizing polymer network **32** to generally lie within a distance d_{poly} of the anisotropic alignment surface **24**. As diagrammatically indicated in FIGURE 1, some polymer chains may reside or extend beyond the distance d_{poly}. By employing a non-uniform density of the stabilizing polymer network **32** with a highest density near the anisotropic alignment surface **24**, the stabilizing polymer network **32** effectively stabilizes the uniformly lying helix texture without producing substantial residual birefringence, optical scattering, or

other deleterious effects. The overall mass of the stabilizing polymer network **32** is reduced, enabling a reduction in the amount of source material. The monomer concentration dissolved into the liquid crystal material **30** before optical polymerization preferably is less than about 5 weight percent (5wt%) of the liquid crystal material **30**, and more preferably is less than about 3 weight percent (3wt%) of the liquid crystal material **30**.

FIGURE 1 shows a surface-stabilized electro-optic device, in which the anisotropic alignment surface **24** serves as an alignment surface and the stabilizing polymer network **32** is substantially confined to within the distance d_{poly} of the anisotropic alignment surface **24**. In other words, the electro-optic device includes a liquid crystal bulk layer and a surface sub-region containing the stabilizing polymer network **32**. This device is suitably referred to as a surface-stabilized chiral or cholesteric electro-optic device.

With reference to FIGURES 2 and 3, other suitable electro-optic devices are shown. In FIGURES 2 and 3, components corresponding to components of FIGURE 1 are labeled with similar primed and double-primed reference numbers, respectively. Thus, the exemplary electro-optic device of FIGURE 2 includes a liquid crystal cell **10'** with two spaced apart principal confining substrates **12'**, **14'** having facing confining surfaces defining a gap **G'**, confining side surfaces **16'**, **18'**, electrodes **20'**, **22'**, and a liquid crystal material **30'** disposed within the gap **G'**. Similarly, the exemplary electro-optic device of FIGURE 3 includes a liquid crystal cell **10''** with two spaced apart principal confining substrates **12''**, **14''** having facing confining surfaces defining a gap **G''**, confining side surfaces **16''**, **18''**, electrodes **20''**, **22''**, and a liquid crystal material **30''** disposed within the gap **G''**.

The surface-stabilized electro-optic device of FIGURE 2 differs from the electro-optic device of FIGURE 1 primarily in that both principal confining substrates **12'**, **14'** have alignment surfaces. The confining substrate **14'** has an anisotropic alignment surface **24'** formed by rubbing or another process, while the confining surface **12'** has an anisotropic alignment surface **64**. During the optical polymerization, first ultraviolet light **46'** illuminates the gap **G'** through the principal confining substrate **14'** with ultraviolet light intensity profile **50'**, and produces a first stabilizing polymer network portion **32'** generally extending a distance d_{poly}' into the gap **G'**. A second

ultraviolet light 66 illuminates the gap G' through the principal confining substrate 12' with ultraviolet light intensity profile 70, and produces a second stabilizing polymer network portion 72 generally extending a distance $d_{poly,2}$ into the gap G'. Thus, the stabilizing polymer network 32', 72 has a higher density near each alignment surface 24', 64' and a lower density near a center of the gap G'. It will be appreciated that the ultraviolet light intensity profiles 50', 70 and corresponding distances d_{poly}', $d_{poly,2}$ may be different, although for simplicity they are drawn to be substantially similar in exemplary FIGURE 2. The electro-optic device shown in FIGURE 2 is suitably referred to as a double-surface-stabilized chiral or cholesteric electro-optic device.

In contrast to the surface-stabilized devices of FIGURES 1 and 2, the electro-optic device shown in FIGURE 3 is a volume-stabilized device in which the polymer network extends throughout the liquid crystal layer and is substantially uniform throughout the liquid crystal layer.

The electro-optic device of FIGURE 3 differs from the electro-optic device of FIGURE 1 primarily in that ultraviolet light 46" used in the optical polymerizing process has a photon energy or free-space wavelength selected to substantially reduce absorption in the liquid crystal material 30". Hence, a substantially spatially uniform ultraviolet light intensity profile 50" produces a stabilizing polymer network 32" that is substantially uniform across the gap G". This arrangement is suitably referred to as a volume-stabilized chiral or cholesteric electro-optic device. In the electro-optic device of FIGURE 3, each principal confining substrate 12", 14" has an anisotropic alignment surface 24", 84 for aligning the liquid crystal 30". However, it is also contemplated to have only one of the confining substrates include an anisotropic alignment surface for aligning the liquid crystal.

For typical liquid crystal materials, spatially non-uniform polymer networks such as the networks 32, 32', 72 of FIGURES 1 and 2 are produced using ultraviolet light having a photon energy that is preferably greater than about 3.55 eV, and that is more preferably greater than about 3.8 eV. For lower photon energies, the ultraviolet light is typically less strongly absorbed by the liquid crystal, producing a substantially spatially uniform polymer network such as the stabilizing polymer network 32" of FIGURE 3. Based on Equation (1), it will also be appreciated that the extent d_{poly}, of the stabilizing polymer network 32 or the extent d_{poly}', $d_{poly,2}$ of the

stabilizing polymer network portions **32'**, **72** depends upon the initial intensity I_o of the ultraviolet illumination.

Those skilled in the art can select a suitable wavelength and initial illumination intensity to produce a selected polymer network configuration in a gap of a specific size filled with a specific liquid crystal based on the absorption coefficient versus wavelength or photon energy characteristic of the liquid crystal material. Because the concentration of the monomer is typically low (for example, less than about 5wt% of the liquid crystal material), the absorption coefficient of the liquid crystal material is typically not changed significantly by the dissolving of the monomer therein. In cases where the monomer incorporation significantly alters the absorption coefficient, or where scattering centers in the liquid crystal create additional scattering optical losses, or so forth, those skilled in the art can readily measure the absorption coefficient change and adjust the ultraviolet light intensity or wavelength, or both, accordingly.

The liquid crystal material **30**, **30'**, **30"** is preferably a chiral or cholesteric liquid crystal that exhibits a flexoelectric response to a relatively small electric field applied by the electrodes **20, 22, 20', 22', 20", 22"**. That is, starting with the electrically unbiased uniformly lying helix texture, application of a small electric field flexoelectrically produces a field-induced deviation of the optic axis. This deviation is typically approximately linear for relatively small applied fields, and is typically governed by:

$$\varphi \cong \frac{eEp}{K} \tag{2},$$

where ϕ is the field-induced angular deviation of the optic axis, E is the magnitude of the electric field applied perpendicular to the principle confining substrates **12, 14, 12', 14', 12", 14"**, p is the pitch of the chiral or cholesteric liquid crystal **30, 30', 30"**, the parameter e is given by:

$$e = \frac{1}{2}\left(e_s + e_b\right) \tag{3},$$

where e_s and e_b are average values of the splay and bend flexoelectric coefficients, respectively, and the parameter K is given by:

$$K = \frac{1}{2}(K_{11} + K_{33}) \qquad (4),$$

where K_{11} and K_{33} are the splay and bend elastic constants, respectively.

At higher electric fields, a quadratic effect is produced by dielectric coupling. At these higher electric fields, the helix begins to deform while the pitch increases. When the applied electric field exceeds a certain critical value, the helix is substantially completely unwound, producing a homeotropic texture when the liquid crystal has positive dielectric anisotropy.

Advantageously, because of the stabilizing polymer network **32, 32', 72, 32''** the liquid crystal **30, 30', 30''** returns to the initial uniformly lying helix texture after the applied electric field is removed. In some preferred electro-optic devices the gap **G, G'** is about 5 microns, and a thickness of the stabilizing polymer network **32** or of the combined stabilizing polymer network portions **32', 72** is less than or about 1 micron. Typically, a thickness or combined thickness of the stabilizing polymer network is suitably about 10% of the total gap to provide stabilization of the uniformly lying helix texture. Those skilled in the art can readily adjust these exemplary dimensions for particular density profiles of the stabilizing polymer network, for ordered stabilizing polymer networks in which the polymer chains are partially or substantially aligned or otherwise ordered, or the like.

Typically, surface-stabilized or double-surface-stabilized chiral or cholesteric electro-optic devices such as the exemplary devices of FIGURES 1 and 2 are particularly suitable for operation in polar mode, in which flexoelectric coupling with the applied electric field is of dominant. Volume-stabilized chiral or cholesteric electro-optic devices such as the exemplary device of FIGURE 3 are particularly suitable for operation in quadratic mode, in which the dielectric coupling is dominant.

For electro-optic devices operating in the visible range, the liquid crystal material preferably exhibits a chiral or cholesteric phase with a short helix pitch preferably less than about 0.5 microns, and more preferably between about 0.2 microns

and about 0.5 microns. The liquid crystal preferably exhibits a pronounced flexoelectric response, and preferably has a positive dielectric anisotropy in a range of about 0.1-10. The liquid crystal material in the chiral or cholesteric phase is preferably a highly birefringent material, having a large Δn in a range of about 0.1-0.5. Optionally, the liquid crystal material exhibits a sign reversal of the dielectric anisotropy with frequency of the applied electric field.

In one example of a volume-stabilized chiral or cholesteric electro-optic device, electro-optical liquid crystal cells each having a 2 micron gap were obtained from EHC Co. Ltd. (Tokyo, Japan). Inner surfaces of the liquid crystal cells wee treated for anti-parallel alignment by forming uniaxially rubbed polymide layers assembled at 180° with respect to the rubbing directions. A short-pitched cholesteric liquid crystal material mixture was formed with the following composition:

69.75wt% MLC6080 eutectic nematic;

25wt% chiral dopants, including a 3:3:1 ratio of CE1, CB15, and R1011;

5wt% RM257 photoreactive monomer; and

0.25wt% Irgacure 651 photoinitiator.

These components are all available from Merck & Co., Inc. (Whitehouse Station, New Jersey), except for the Irgacure 651 photoinitiator which is available from Ciba Specialty Chemicals (Basel, Switzerland). The liquid crystal cells were filled with the short-pitched cholesteric liquid crystal material mixture by a capillary action, and heated to isotropic temperature of the cholesteric. During cool down to room temperature, a 6.26V, 26 Hz square wave electrical voltage bias was applied across the liquid crystal cell to achieve a uniformly lying helix texture. The optical polymerizing was performed using 365 nm ultraviolet illumination at 0.04 mW/cm^2 for thirty minutes at room temperature. The selected ultraviolet illumination provided substantially uniform illumination across the 2 micron gap to produce a volume polymer network, similarly to the optical polymerizing process illustrated in FIGURE 3.

To test for residual birefringence due to the volume polymer network, the electro-optic device was biased at 0 volts, 10 volts, and 25 volts to completely unwind the cholesteric liquid crystal to produce a homeotropic texture. Advantageously, the relatively loose polymeric network produced by the low 5wt% monomer exhibited

no residual birefringence from the polymer network at 25 volts when viewed using crossed polarizers.

With reference to FIGURE 4, electro-optic switching properties of the volume-stabilized chiral or cholesteric electro-optic device in the in-plane flexoelectric switching mode were characterized using a digital oscilloscope. A turn-on or rise time of 60 microseconds and a turn-off or decay time of 120 microseconds was observed for a 2 volt/micron, 110 Hz square wave electrical input.

With reference to FIGURE 5, a 1 volt/micron, 110 Hz triangle wave was applied to a 2 micron volume-stabilized liquid crystal cell to characterize homogeneous in-plane switching characteristics. FIGURE 5 shows a digital oscilloscope plot of the triangle wave input and the transmitted light intensity versus time. The transmitted light measurement indicates symmetric in-plane switching due to moderate positive dielectric anisotropy of the cholesteric liquid crystal material. Preferably, the cholesteric liquid crystal should have a dielectric anisotropy near zero.

In one example of a double-surface-stabilized chiral or cholesteric electro-optic device, electro-optical liquid crystal cells were prepared and filled with a short-pitched cholesteric liquid crystal material mixture in the same way as for the volume-stabilized electro-optic device fabrication, and were heated to isotropic temperature of the cholesteric. During cool down to room temperature, a 9.5V, 22 Hz square wave electrical voltage bias was applied across the liquid crystal cell to achieve a uniformly lying helix texture. The optical polymerizing was performed using 322 nm ultraviolet illumination at $0.08 \, mW/cm^2$ applied from both principal surfaces, similarly to the optical polymerizing process shown in FIGURE 2, for five minutes at room temperature. The selected ultraviolet illumination provides formation of the polymer network adjacent the illuminated principal surfaces. Compared with the 365 nm ultraviolet light used in the optical polymerizing to produce a volume polymer network, a higher absorption of the shorter wavelength 322 nm ultraviolet light resulted in substantially no optical polymerization near the center of the liquid crystal cell gap. Thus, the shorter wavelength 322 nm ultraviolet light provided a double-surface stabilization polymer network as illustrated in FIGURE 2, rather than a volume stabilization polymer network as illustrated in FIGURE 3.

To test for residual birefringence due to the surface polymer network portions, the electro-optic device was biased at 0 volts, 10 volts, and 25 volts to completely unwind the cholesteric liquid crystal to produce a homeotropic texture. Advantageously, the polymeric network portions disposed adjacent the confining surfaces exhibited no residual birefringence from the polymer network at 25 volts when viewed using crossed polarizers.

With reference to FIGURE 6, electro-optic switching properties of the double-surface-stabilized chiral or cholesteric electro-optic device in the in-plane flexoelectric switching mode were characterized using a digital oscilloscope. A turn-on or rise time of 70 microseconds and a turn-off or decay time of 100 microseconds was observed for a 3.5 volt/micron, 110 Hz square wave electrical input.

With reference to FIGURE 7, a 3.5 volt/micron, 110 Hz triangle wave was applied to characterize homogeneous in-plane switching characteristics. FIGURE 7 shows a digital oscilloscope plot of the transmitted light intensity versus time. The transmitted light measurement indicates symmetric in-plane switching due to moderate positive dielectric anisotropy of the cholesteric liquid crystal material. Preferably, the cholesteric liquid crystal should have a dielectric anisotropy near zero, in which case the linearity of the polar flexoelectro-optic response substantially improves.

The invention has been described with reference to the preferred embodiments. Obviously, modifications and alterations will occur to others upon reading and understanding the preceding detailed description. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

Having thus described the preferred embodiments, the invention is now claimed to be: